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# Frost Damage of Roof Tiles: A Study on Moisture Boundary Conditions

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**Abstract**

Freeze–thaw cycles are the most serious cause of roof tile deterioration; thus, it is important to know the temperature and moisture distributions in tile materials for protection against frost damage. This study focused on moisture boundary conditions for air layers under the tile. Temperature and humidity were measured using model structures with different types of roof tiles. The results showed that the temperatures around the roof were strongly influenced by solar and longwave radiation, and the humidity in the air layer was close to the outdoor. The ventilation rate between the outdoor and the air layer was estimated by numerical modelling based on the measured results.



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*Keywords:* Frost damage; Roof tile; Moisture boundary condition; Air layer; Ventilation rate; Emissivity

## 1. Introduction

Freeze–thaw cycles are the most serious cause of roof tile deterioration. The freezing point of water in porous materials (e.g. roof tiles) is depressed by the capillary pressure, which depends on the diameter of the pores [1]. When the pores are saturated, the freezing point is assumed to be same as that of water (0 °C). The moisture adsorption under specific relative humidity also depends on the pore diameter. Freezing depends on the temperature and moisture content of the material. Thus, knowing the temperature and moisture distribution in the material is important for protection from frost damage.

We conducted a field survey on the deterioration of fence roof tiles in the old temple precinct of Kyoto, Japan. Several types of deterioration were observed, including cracks, flaking and delamination [2]. The different damage

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features were attributed to various causes, such as tile strength anisotropy and the temperature and moisture distribution in the tile.

This study focuses on differences in moisture boundary conditions owing to the roof tile structure. In one structure, which was evaluated in a previous survey [2], roofing soil was placed under the tile, whereas in another structure, the roof tiles were hung on the tile battens without roofing soil but with an air layer beneath them. Since very little moisture in the tiles evaporates through the back surface when soil is placed underneath them, the moisture content in the region near the back surface may be high. Survey results in winter suggested that the roof tiles and roofing soil might contain sufficient water for freezing, especially when water could easily penetrate them.

The purpose of this study is to clarify the temperature and humidity in the back air layer by an experiment using scaled model structures with different types of roof tiles and by numerical modelling.

**Nomenclature**

| | | | |
|---|---|---|---|
| $c$ | specific heat [J/kg K] | $n$ | ventilation rate [1/s] |
| $S$ | area [m$^2$] | $t$ | time [s] |
| $T$ | temperature [K] | $V$ | volume [m$^3$] |
| $X$ | humidity ratio [kg/kg'] | $\alpha$ | heat transfer coefficient [W/m$^2$K] |
| $\alpha'$ | moisture transfer coefficient [kg/m$^2$s(kg/kg')] | $\varepsilon$ | emissivity [-] |
| $\rho$ | density [kg/m$^3$] | | |
| subscript; | | | |
| $a$ | air layer | $o$ | outdoor air |
| $rt$ | roof tile | $rb$ | roofing board |
| $c$ | convective | $r$ | radiative |
| $b$ | back surface | $u$ | upper surface |

## 2. Experiment with a roof model

### *2.1. Experimental setup and measuring point*

Figure 1 (a) shows model roof structures with different types of tiles: No.1 used oxidized silver tile (Japanese-style), No.2 used glazed tile (flat type) and No.3 used decorative slate. Silver and glazed tiles had back air layers due to their shape (see Fig. 1 (b), (c)). Decorative slate had very thin air space because it was directly nailed onto the roofing board. Silver tile was entirely coated in a thin carbon film for waterproofing and appearance, and it had a lower absorptivity of longwave/shortwave (solar) radiation than the other two roofing materials. A low-emissivity roofing sheet with aluminium foil was used only in the No.2 model; ordinary asphalt roofing was used in the No.1 and No.3 models.

These model roofs were set onto the rooftop of a building on the Kyoto University campus. There were not high buildings around the building; thus, the experimental setup was fully open to the sky. Each model structure had two roof surfaces: one was facing south and the other north; each roof area was approximately 1 square meter. The slope of each roof was about 22°.


Fig. 1. Experimental setup: (a) Roof model structures; (b) Back air layer of Japanese-style tile; (c) Back air layer of flat type tile

Cross-sections of the roof structures and the measuring points are shown in Fig. 2. The thickness of the roof tile ranged from 12 to16 mm, and that of the decorative slate was 5.2 mm.

The surface and back temperatures of the roof material and the roofing board were measured using T-type thermocouples. Temperature and humidity sensors were set in the south and north-facing air layers, respectively, in the No.1 and No.2 models. Weather conditions such as outdoor temperature and humidity, global solar radiation, wind speed and direction, and precipitation were also measured near the roof model structures. Data on each metric were logged every 10 min. The north-facing roof of the No.1 model was photographed at regular intervals to check the surface wetting and snow cover condition.

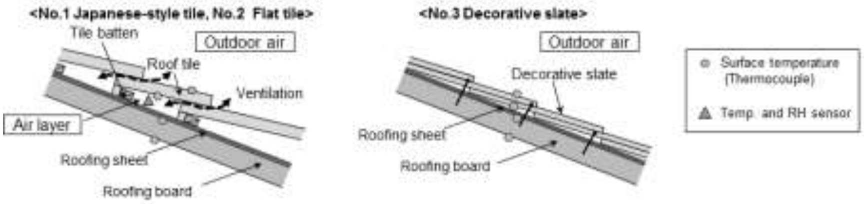
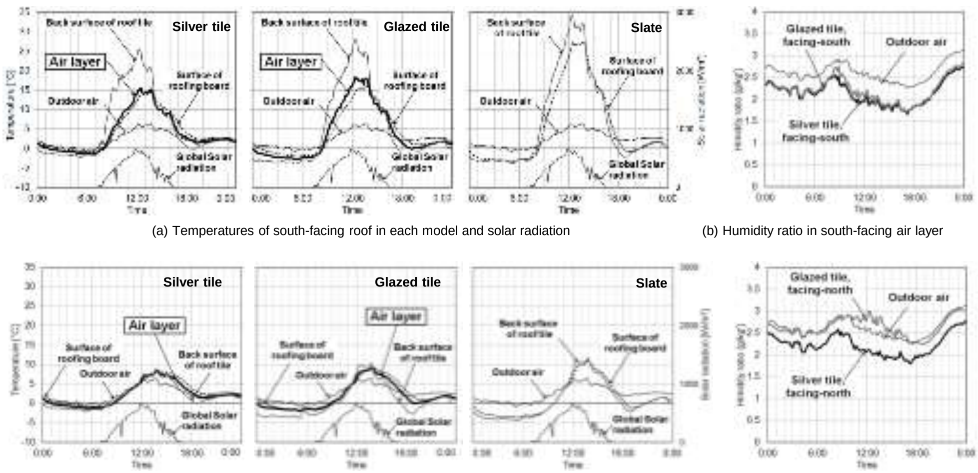



Fig. 2. Section of the roof model and measuring points.

## 2.2. Measurement results

Although the experiment lasted over one year, the results for the winter season related directly to frost damage were focused upon in this paper. Fig. 3 shows the temperatures of the tile surface, air layer and roofing board for each model and the humidity ratio in the air layer for the No.1 and No. 2 models on a sunny winter day (22 December, 2014).




(a) Temperatures of south-facing roof in each model and solar radiation

(b) Humidity ratio in south-facing air layer

(c) Temperatures of north-facing roof in each model and solar radiation

(d) Humidity ratio in north-facing air layer

Fig. 3. Temperatures of tile surface, air layer and roofing board and humidity ratio in air layer on a typical sunny winter day.

Since the solar altitude is low in winter, the solar heat gained in daytime was significantly different between the southern and northern surfaces, and the temperature in the southern air layer became higher than that in the northern air layer. The temperature of the glazed tile was slightly higher than that of silver tile because of higher solar absorptivity. However, the roofing board temperatures in both roof types changed similarly because the roofing sheet used with glazed tile had a high long-wave reflectivity. The slate was thinner than the roof tiles and did not have the back air layer, thus solar radiation heat absorbed by the slate was directly conducted to the roofing board.

During the nighttime, the surface temperature of the roof material in each model dropped below the outdoor temperature due to the nocturnal radiation. Among them, the degree of temperature drop in silver tile was smaller than the other two types because of low long-wave emissivity. The temperatures around the roof were strongly influenced by solar and longwave radiation.

Fig. 4 shows the correlation between the outdoor humidity and the air layer humidity during two winter months, December 2014 and January 2015. The humidity in the air layer was close to the outdoor humidity, but slightly smaller than the outdoor humidity on sunny day (as shown in Fig. 3 (b), (d)). This suggests that relatively dry condition is kept in the air layer in winter.

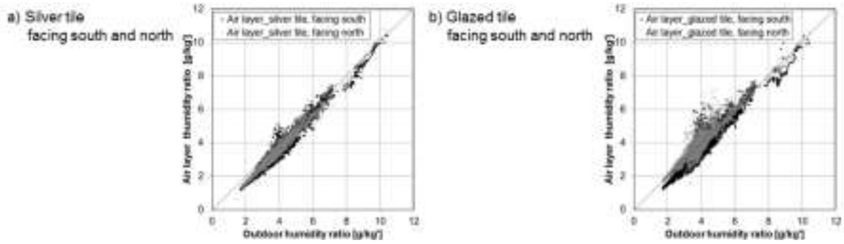



Fig. 4. Humidity ratios in the air layers in the (a) No. 1 and (b) No. 2 models during two winter months.

## 3. Numerical modelling of temperature and humidity of air layer

### 3.1. Calculation model

To estimate the temperature and humidity of the air layer, a simple, one-dimensional model in Fig. 5 was proposed. The gap at the overlapping area was assumed to be a ventilation passage. In this model, convective heat transfer, longwave radiation, solar radiation and heat transfer through air exchange were considered. Vapor transmission was calculated, although rain penetration through the roof tile surface and water flow through the overlapping area were not taken into consideration. Radiative heat transfer between the back surface of the tile and the upper surface of the roofing sheet was calculated assuming infinite two parallel planes [4]. Measured weather data and the back surface temperature of the roofing board were used as boundary conditions in this calculation.

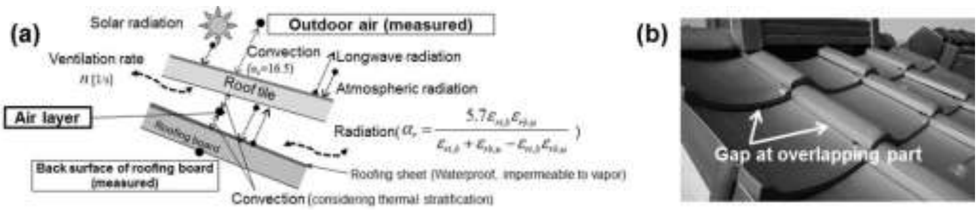



Fig. 5. Calculation model: (a) Calculation conditions. (b) Gap assumed to be ventilation passage.

The temperature and humidity distributions inside the roofing tile and roofing board were calculated by the simultaneous heat and moisture transport equations proposed by Matsumoto [3]. Equations (1) and (2) present the energy and moisture balance in the air layer, respectively.

$$c_a \rho_a V_a \frac{\partial T_a}{\partial t} = \alpha_{ca}\left(T_{rt,b} - T_a\right)\cdot S_a - \alpha_{ca}\left(T_a - T_{rb,u}\right)\cdot S_a + c_a \rho_a V_a n\left(T_o - T_a\right) \tag{1}$$

$$\rho_a V_a \frac{\partial X_a}{\partial t} = \alpha'_{a,u}\left(X_{rt,b} - X_a\right)\cdot S_a - \alpha'_{a,b}\left(X_a - X_{rb,u}\right)\cdot S_a + \rho_a V_a n\left(X_o - X_a\right) \tag{2}$$

In the present calculation, the material properties of the silver tile were used, as listed in Tables 1.

Table 1. Material properties.

| | Unit | Silver oxidized tile | Roofing board |
|---|---|---|---|
| Thermal conductivity (dry condition) | [W/m K] | 0.397 | 0.160 |
| Specific heat | [J/kg K] | 920 | 1880 |
| Density | [kg/m$^3$] | 1970 | 500 |
| Solar absorptivity on the top surface | [-] | 0.65 | - |
| Longwave emissivity on the top surface | [-] | 0.55 | - |
| Longwave emissivity on the back surface | [-] | 0.55 | - |
| Longwave emissivity on the roofing sheet | [-] | 0.9 | - |
| Thickness | [mm] | 16 | 12 |
| Average thickness of back air layer | [mm] | 50 | - |
| Vapor permeability | [kg/m s Pa] | $3.84\times10^{-12}$ | $2.0\times10^{-12}$ |
| Vapor resistance of surface finish | [m$^2$ s Pa/kg] | $2.68\times10^{10}$ | - |

### *3.2 Estimation of ventilation rate between outdoor air and the back air layer*

Numerical calculation was performed for two winter months (December 2014 and January 2015). First, a case with low ventilation rate (n =1.0 [1/h]) was calculated. Fig. 6 shows the time profile of temperatures (tile surface, air layer, and the roofing board) and the humidity ratio in the air layer for the south-facing roof for three winter days without rain. Although calculated temperature agreed well the measured data, significant discrepancy between measured and calculated humidity ratio was seen especially in daytime. This is because the both surface of the silver tile absorbs moisture in night and desorbs it especially when the tile temperature rises due to solar radiation.

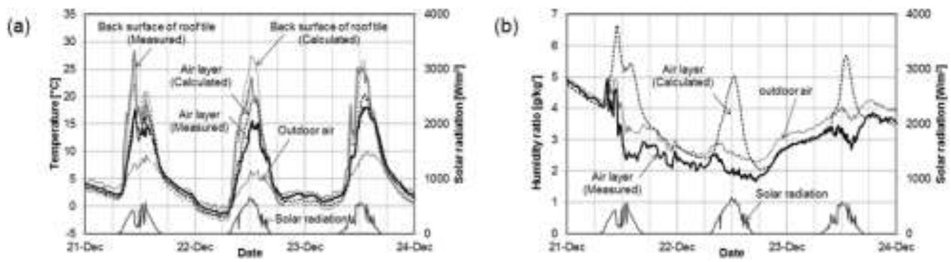



Fig. 6. Measured and calculated results of south-facing roof ($n$ = 1.0): (a) Temperature of tile surface and air layer (b) Humidity ratio in air layer

Then, two cases of calculation with different ventilation rate $n$ (5.0, 10.0 [1/h]) for both south and north-facing roofs were conducted. The temperatures in the air layer did not change significantly with the ventilation rate. Fig. 7 shows the measured and the calculated humidity ratio in the air layer in case with south-facing roof, (a) $n$ = 5.0 [1/h], (b) $n$ = 10.0 [1/h], respectively.

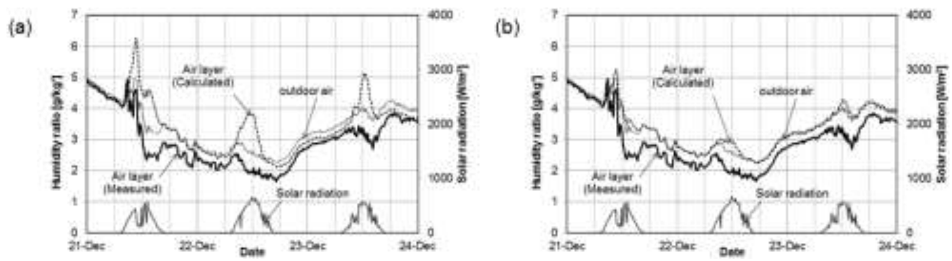



Fig. 7. Measured and calculated humidity ratio in air layer: (a) in case with $n$ = 5.0 [1/h] (b) in case with $n$ = 10.0 [1/h]

When ventilation rate became higher, the peak of calculated humidity ratio decreased and became close to the outdoor humidity. In such cases, the calculated humidity ratio in night time came to disagree with the measured data.

Fig. 8 shows a comparison between the measured and calculated temperature and humidity ratio in the air layer for each value of the ventilation rate, *n*. The temperature in the air layer was mainly influenced by the surface temperature of both sides rather than the ventilation rate. In contrast, the difference between the measured and calculated humidity decreased as the (constant) ventilation rate increased. In north-facing roof, the discrepancy between measured and calculated humidity was not so much even in the case with low ventilation rate.

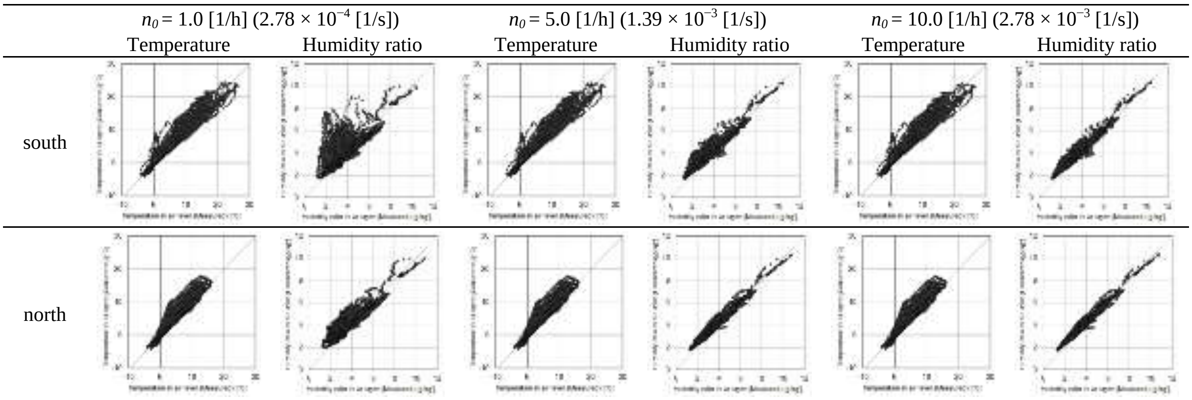



Fig. 8. Measured (X axis) vs. calculated (Y axis) temperature and humidity ratio for each value of the ventilation rate, *n* (in two winter months).

The disagreement between measured and calculated humidity ratio (remarkably found in south-facing roof), mainly occurred when the temperature difference between the outdoor and the air layer was large due to solar radiation. Therefore, it is suggested that the increase in ventilation rate due to temperature difference between the outdoor and the air layer should be taken into consideration.

## 4. Conclusions

The temperature and humidity in the back air layer formed by the roof tile were measured using model structures. From the experimental results, the humidity ratio in the air layer was shown to closely follow the outdoor humidity. The results were also confirmed by the numerical simulation, suggesting that there was a sufficient amount of ventilation in daytime due to the temperature difference between the outdoor and the air layer. Thus desorbed moisture from the tile could be exhausted promptly. The dry condition in the air layer helps to prevent frost damage. In this paper, the case of south-facing silver tile was examined. Along with the calculation results of different roof tiles and orientations, we will clarify the factors influencing temperature and humidity in the back air layer.

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